

Fiber-detector subsystem loss comparison for a ground-based photon-counting optical receiver

Free-Space Laser Communications XXXV

Session 7: Ground Transceiver Technologies II

Brian E. Vyhalek, Sarah A. Tedder

NASA Glenn Research Center

Cleveland, OH

Introduction



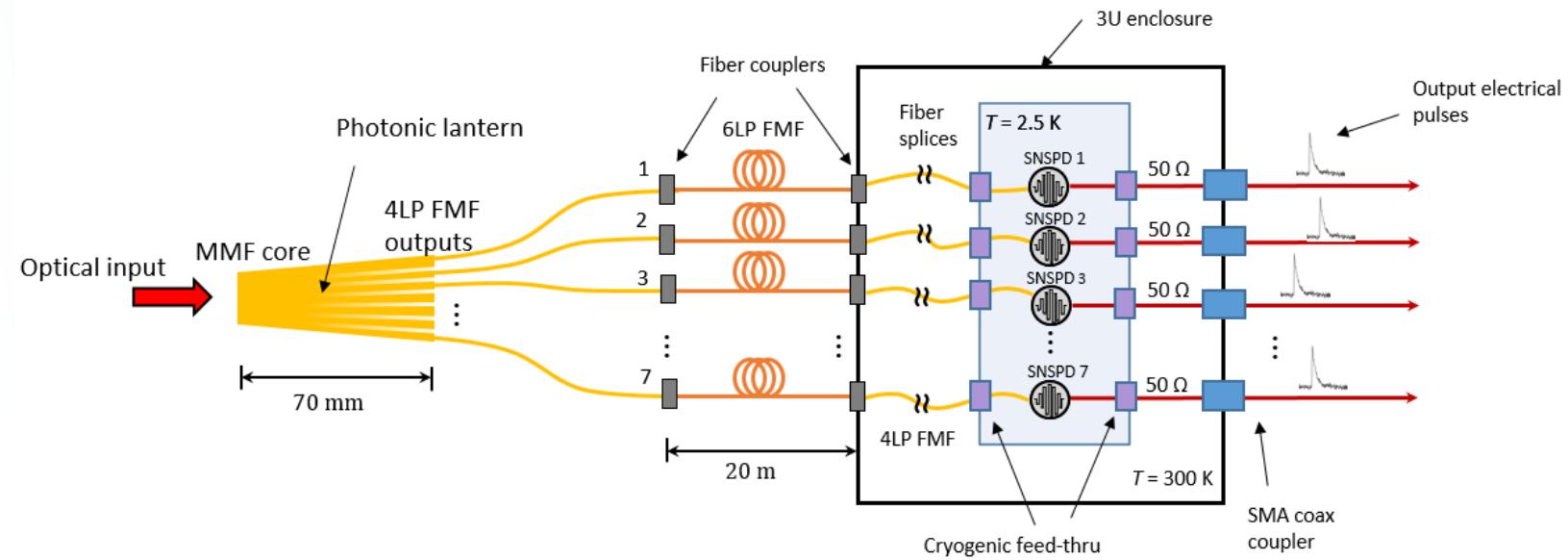
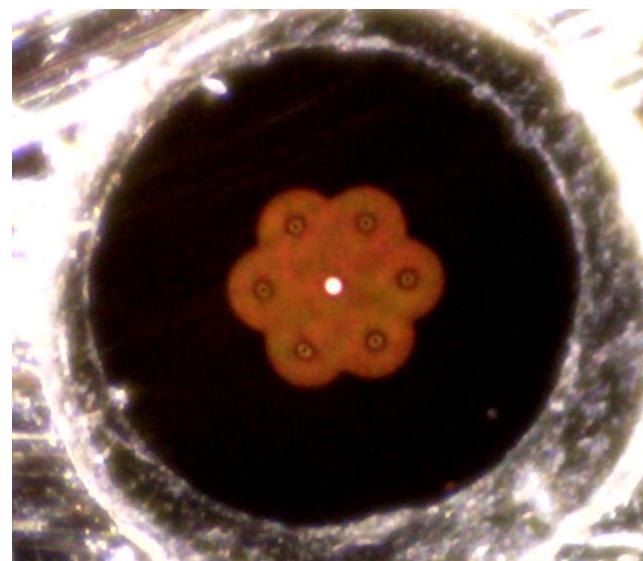
- NASA Glenn is building a photon-counting ground receiver compliant with the CCSDS Optical Communications HPE standard
- Goals:
 - Utilize commercial off the shelf (COTS) components
 - Demonstrate with O2O at the NASA Goddard Low-Cost Optical Terminal (LCOT) ground station
 - Transfer technology to commercial company
- Receiver subsystems are:
 - Fiber interconnect, from telescope to detectors
 - COTS superconducting nanowire single photon detectors (SNSPDs)
 - FPGA on COTS development platform for real-time processing
- Two receiver concepts:
 - Photonic lantern with 1 multi-mode input and 7 few mode fiber (FMF) outputs to 7 single-element COTS SNSPDs
 - A single FMF to a COTS 16-element SNSPD array
- Need to fully characterize system losses

Photonic Lantern + 7 Single Element Detectors



Photonic Lantern:

- **FMFs:**
 - 20 μm graded-index core
 - 4LP, 6-mode
- **MMF input:**
 - 55 μm
 - 42 total modes

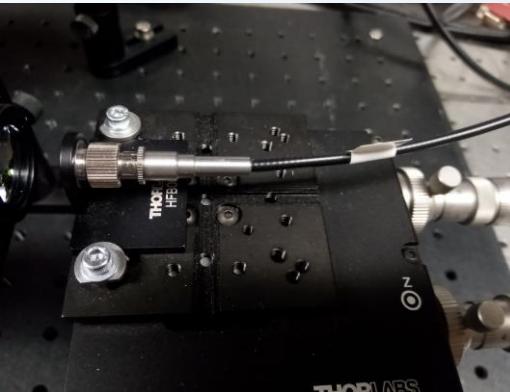


FMF + 16-Channel SNSPD Array



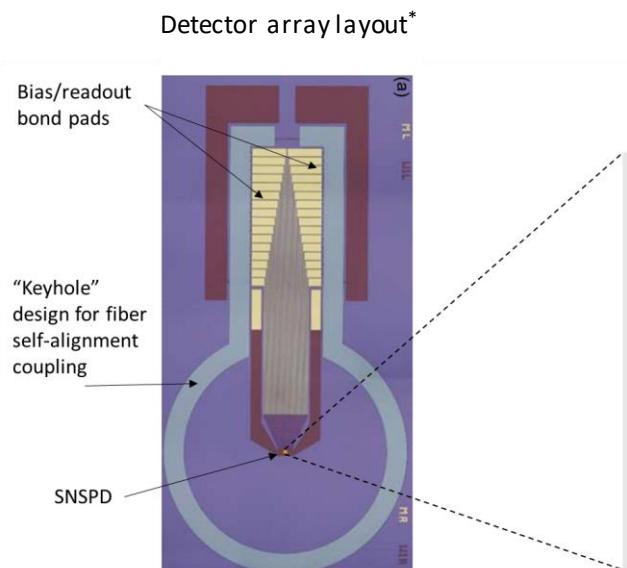
FMF #1 (coupled to SNSPD array):

- **20 μm graded-index core**
- **4 LP, 6-modes**

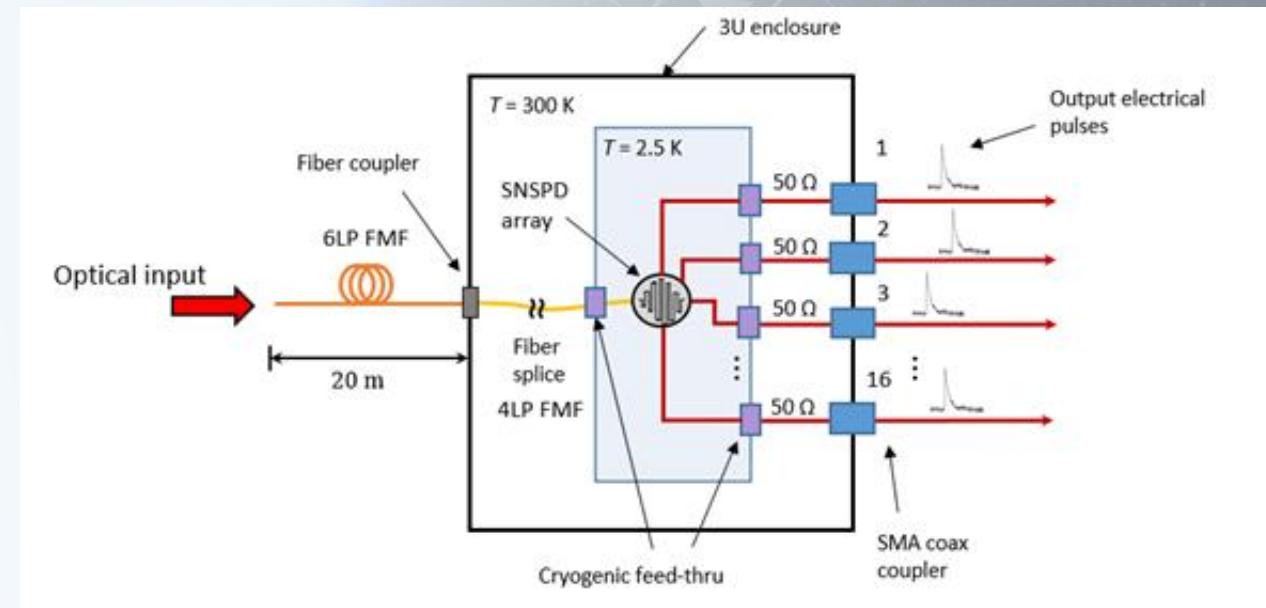


FMF #2 (20 m system input):

- **25 μm graded-index core**
- **6 LP, 10-modes**

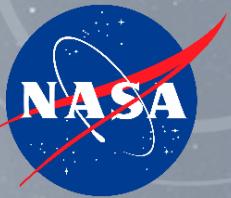


Layout of the SNSPD linear array active area, with each individual element color-coded



*Rambo, T. M., Conover, A. R., and Miller, A. J., "16-element superconducting nanowire single-photon detector for gigahertz counting at 1550-nm," (2021). <https://arxiv.org/abs/2103.14086>

SNSPD Characteristics



Single-Element Detector

Parameter	Value
Efficiency	≈ 80 - 83% max
Dark count rate	< 5 kcps
Polarization loss	1.2 dB
Reset time	15 - 18 ns
Pulse rising edge	≈ 850 ps
Pulse amplitude	600 – 800 mV
Blocking loss*	< 1 dB @ 100 M-ph/s
Count rate (3 dB)*	≈ 160 Mcps @ 400 M-ph/s
Jitter (FWHM)	≈ 60 – 80 ps
Channel skew	< 500 ps

* Aggregate for 7 detectors

16-Channel Array

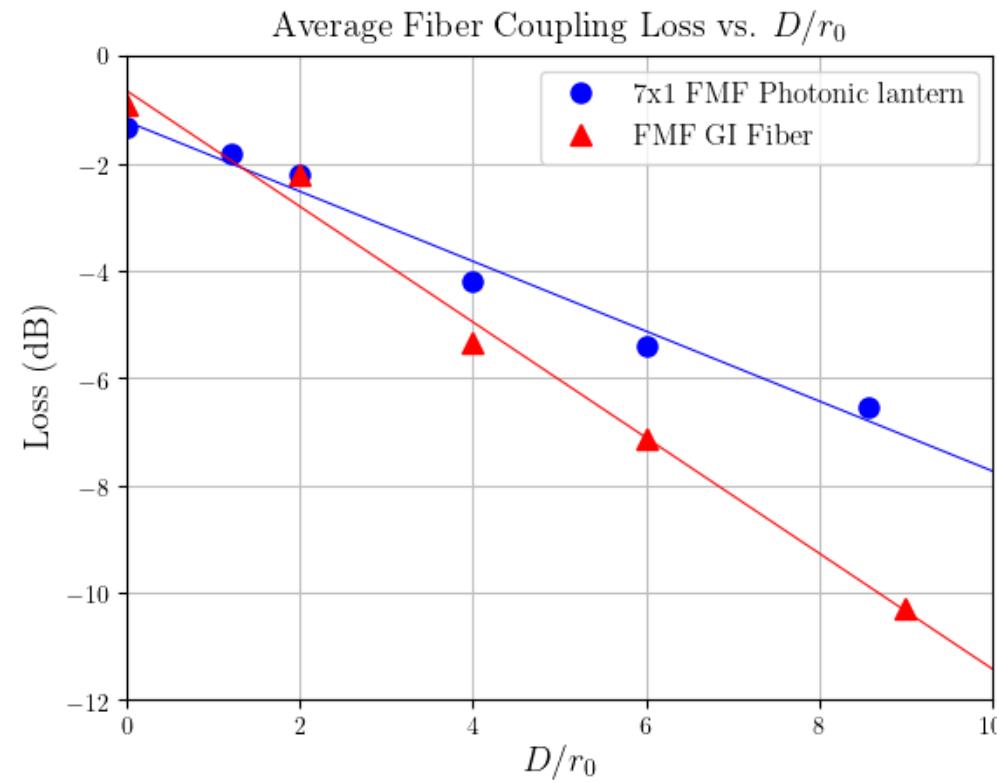
Parameter	Value
Efficiency	≈ 83% max
Dark count rate	3 - 10 kcps
Polarization loss	1.35 dB
Reset time	5 - 8 ns
Pulse rising edge	≈ 500 ps
Pulse amplitude	240 – 300 mV
Blocking loss	< 1 dB @ 300 M-ph/s
Count rate (3 dB)	≈ 500 Mcps @ 1 G-ph/s
Jitter (FWHM)	75 – 95 ps
Channel skew	< 150 ps
Crosstalk probability	< 0.002%

Sources of Loss



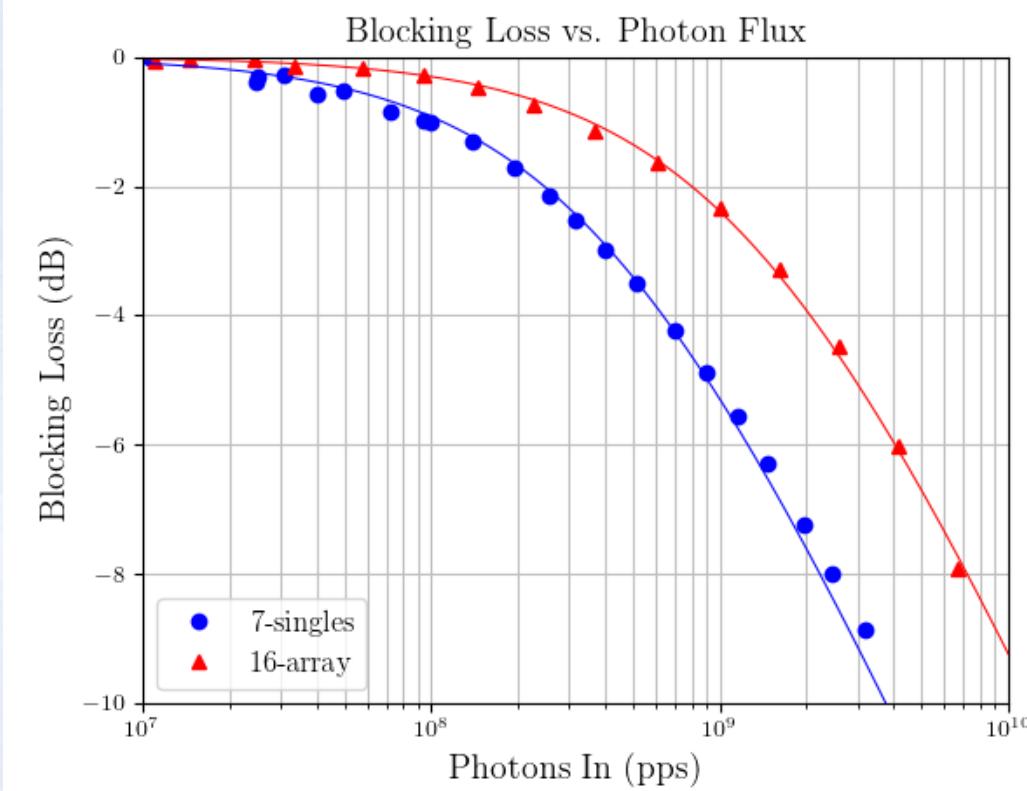
Fiber interconnect:

- Coupling under atmospheric turbulence
- Control of distribution to detectors

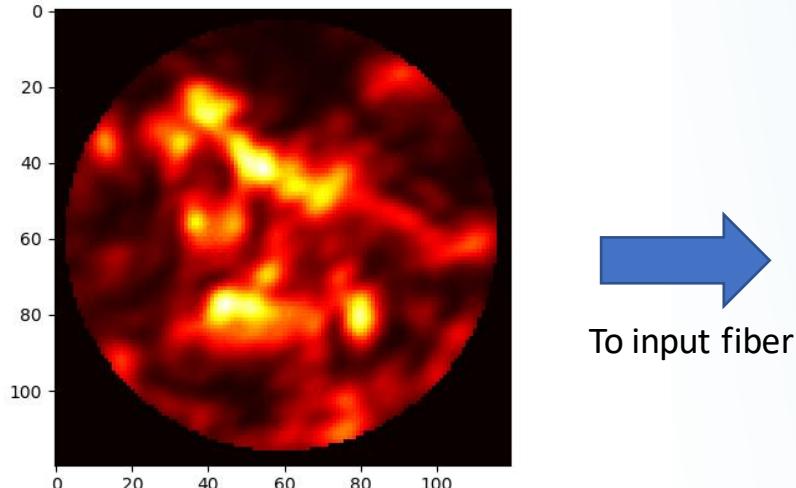


Single-photon detectors:

- Detection efficiency
- Reset time limits count rates
- Depends on input rate (power)

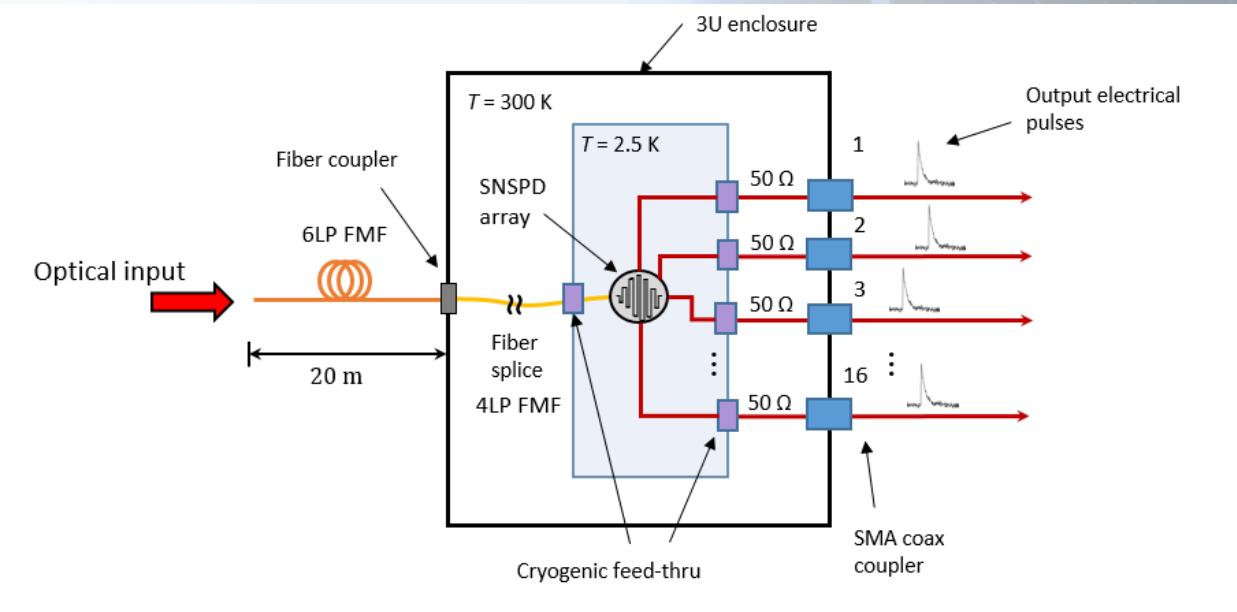


SNSPD Array Count Spatial Distribution



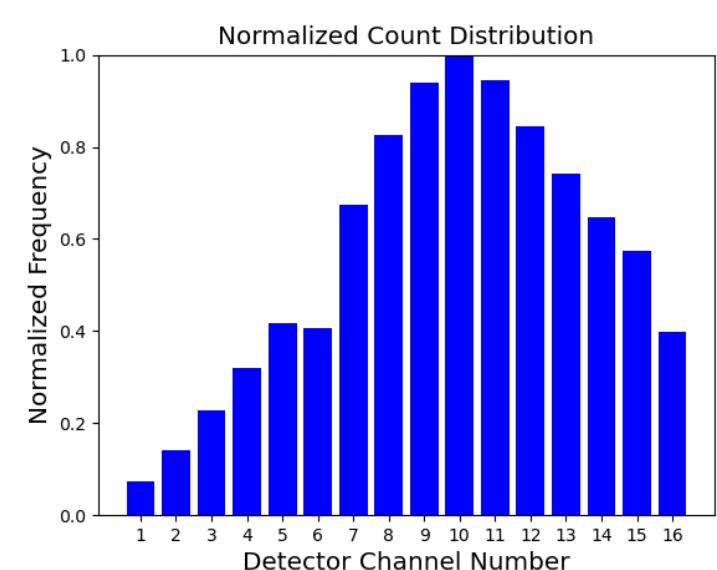
To input fiber

Emulated turbulence intensity profile from
Arbitrary Light Field Generator (ALF-G)

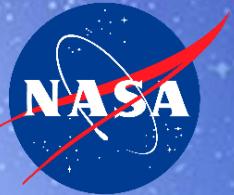


- Emulated wavefront from the ALF-G couples to input 25/20- μm FMF which is coupled to the 16- μm SNSPD array

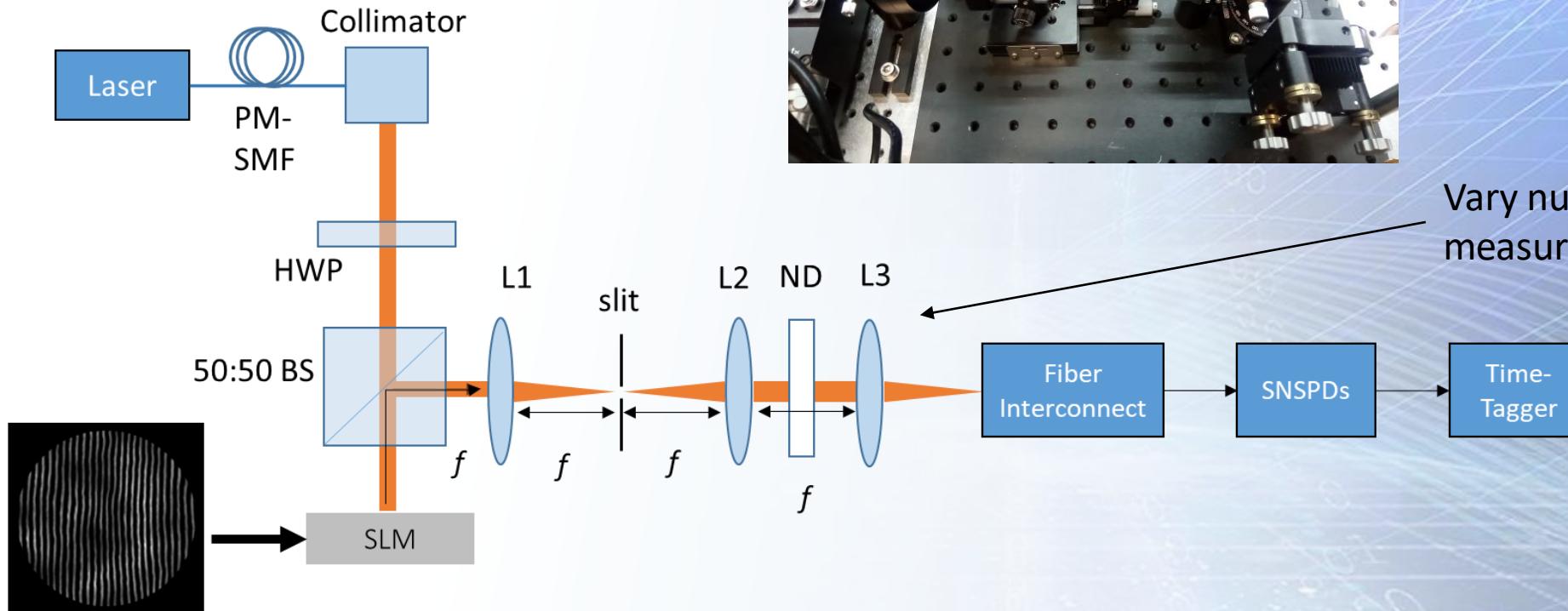
**Linear SNSPD array layout provides 1-D spatial information.
Distributions are in general, non-uniform.**



Arbitrary Light Field Generator (ALF-G)

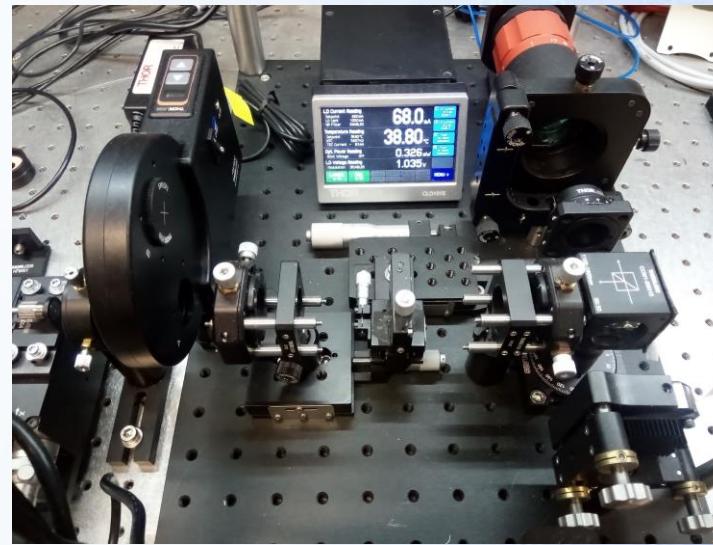


Simulated 2D beam profiles (phase and intensity) are recreated in the lab by modulating the beam via a complex amplitude phase hologram written to the SLM.



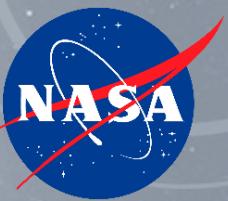
Hologram of beam with
emulated atmosphere

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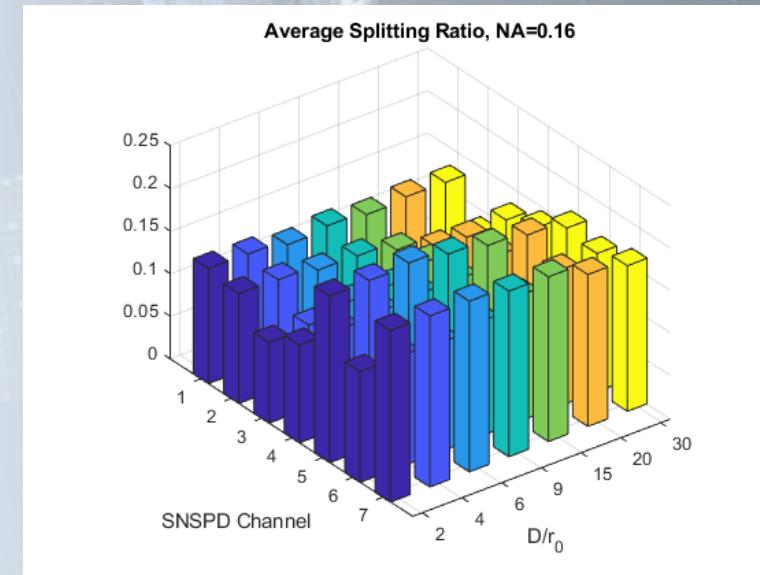
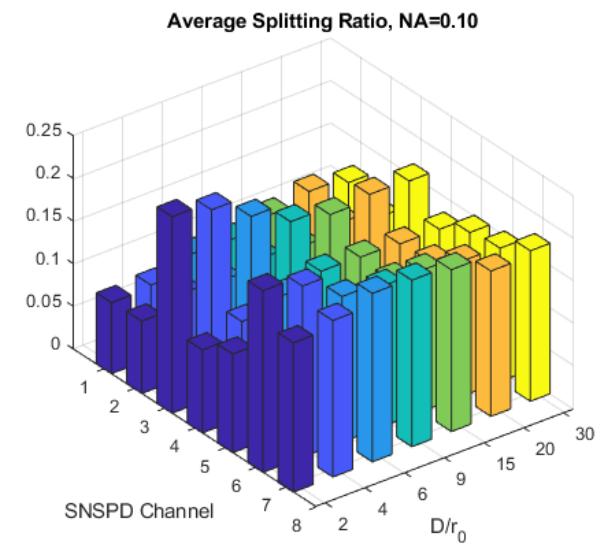
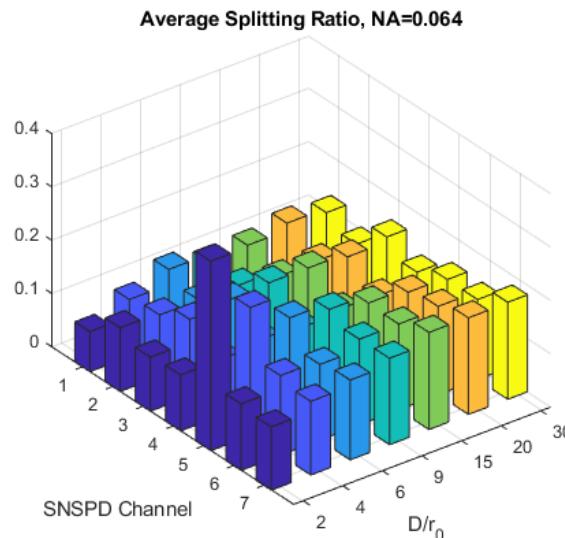


Vary numerical aperture with L3 to measure light distribution on detectors

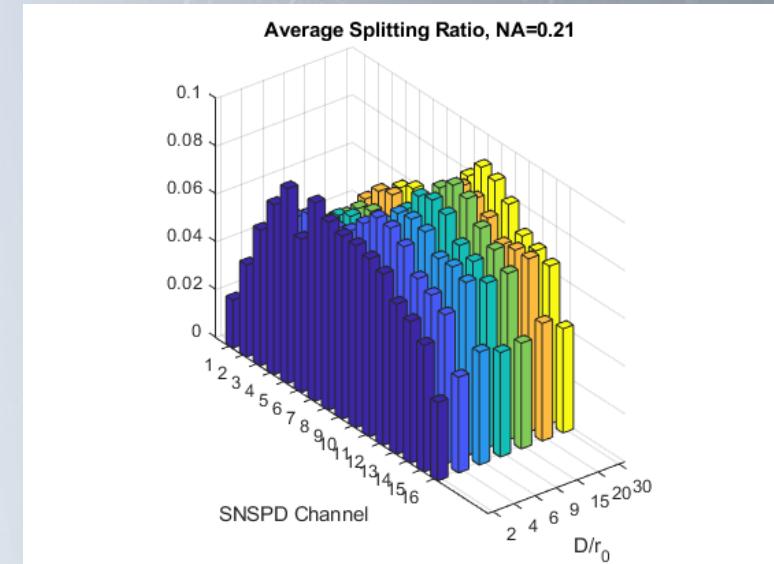
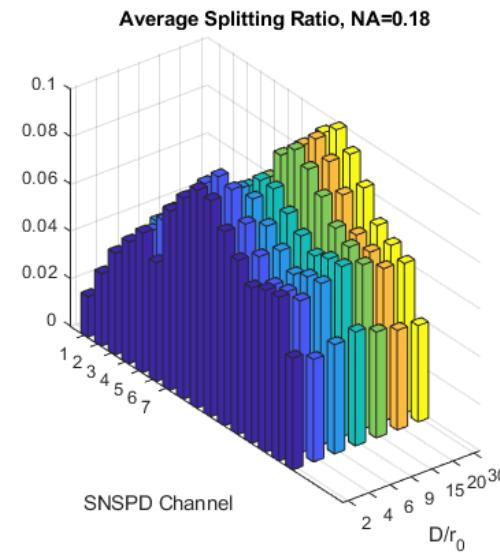
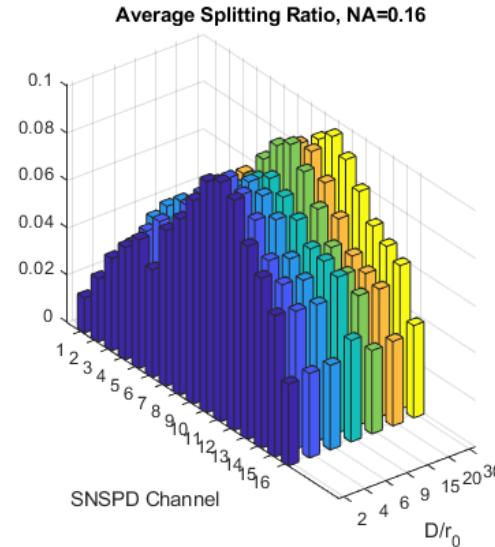
Average Count Rate Distributions



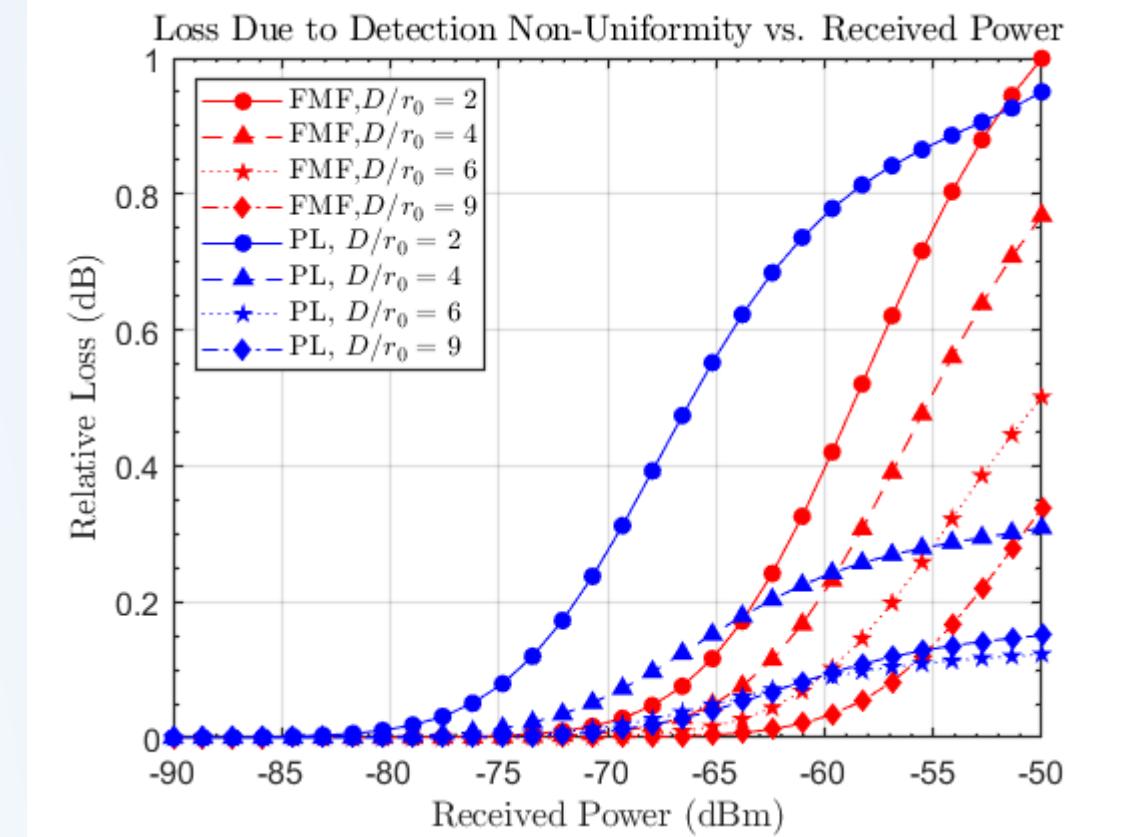
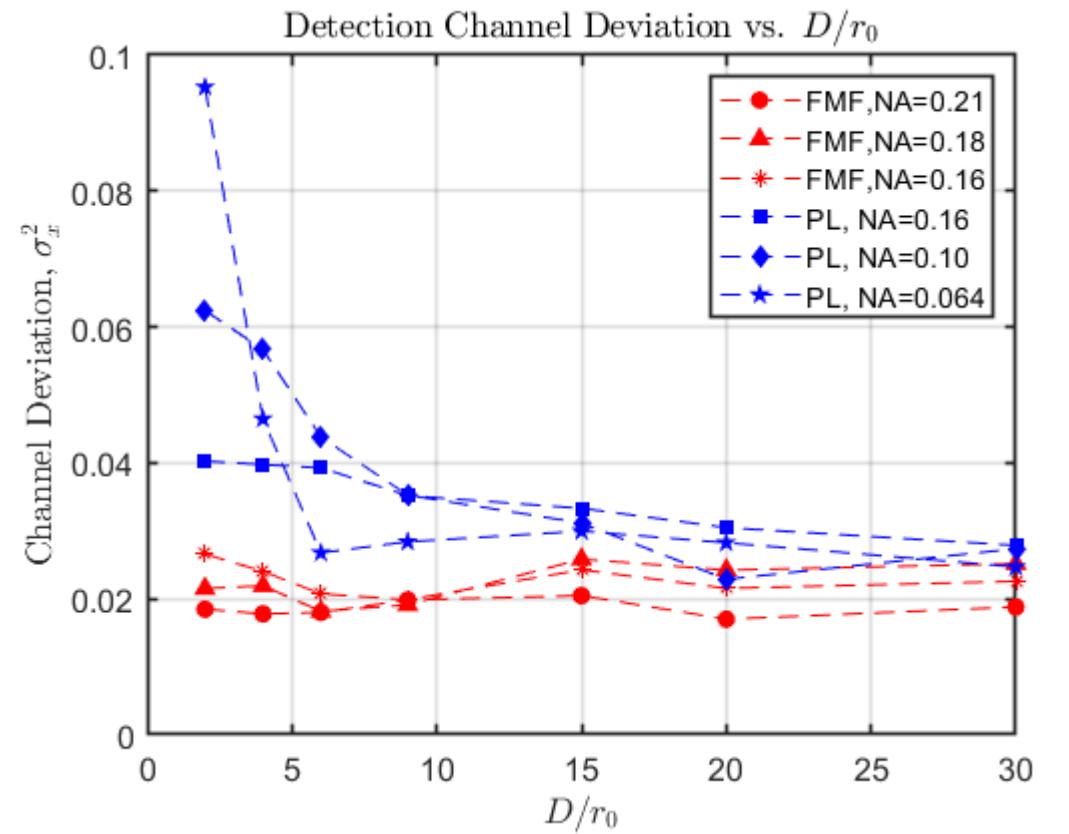
Photonic lantern



FMF

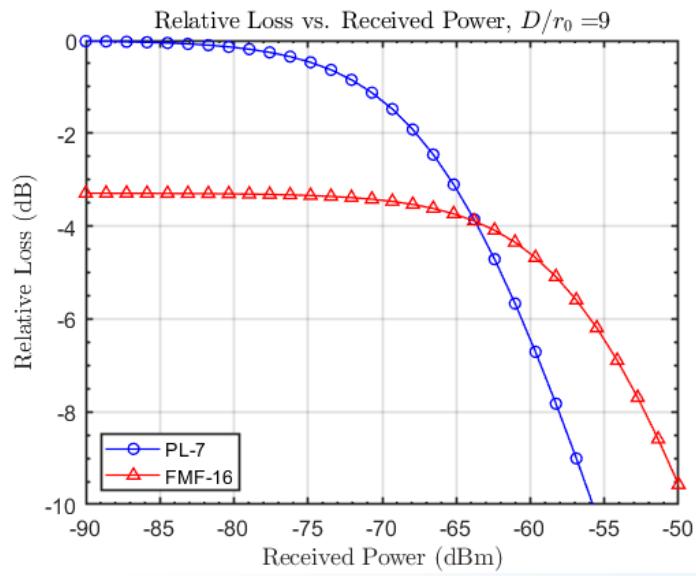
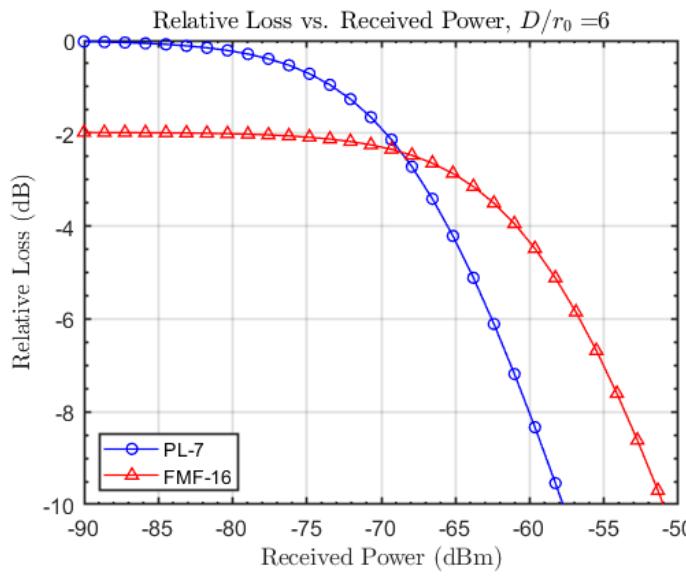
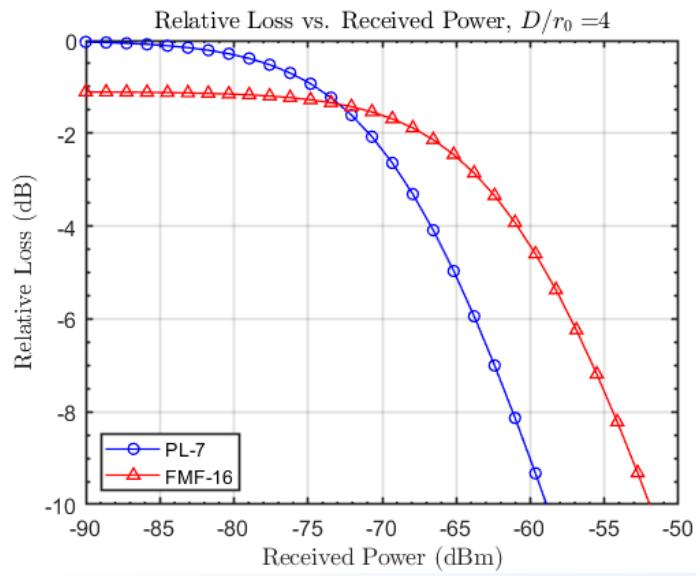
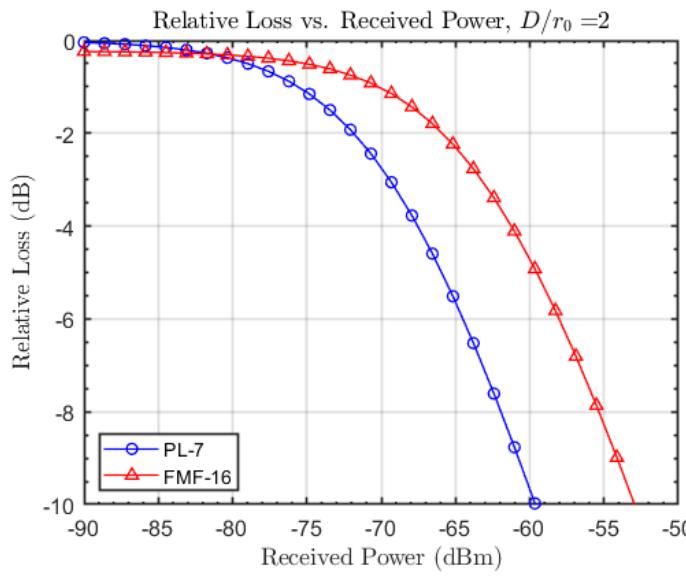


Added Loss From Non-Uniform Distribution



Additional flux dependent loss due to the non-uniformly distributed incident light is less than about 1 dB for all D/r_0

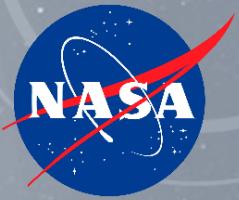
Loss Comparison



D/r_0	Relative Loss (dB)	P_{RX} (dBm)
2	0.20	-81.31
4	1.08	-72.82
6	1.96	-68.78
9	3.28	-63.53

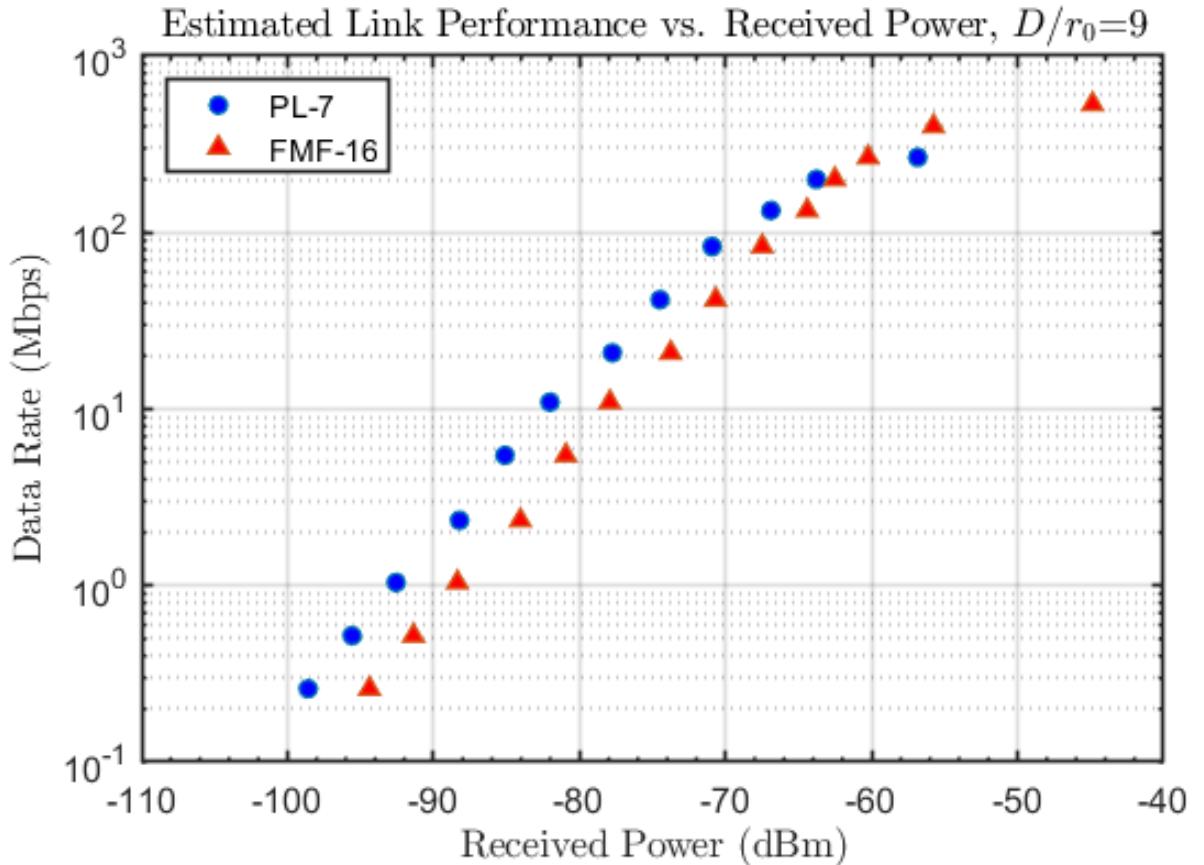
- Combined coupling loss, blocking loss, and input distribution effects over a range of input power
- FMF/SNSPD array system has more loss at lower received power and higher D/r_0 due to coupling
- Photonic lantern/single SNSPDs system has more loss at higher input powers due to detector count rate limitations
- There is a cross-over input power where relative coupling loss balances detector blocking losses

Estimated Link Performance



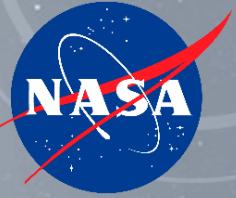
Parameters:

- PPM order
 $M = \{4, 8, 16, 32, 64, 128, 256\}$
- Code rate
 $CR = \{1/3, 1/2, 2/3\}$
- Slot width
 $T_s = \{0.5, 1, 2, 4, 8, 16, 32\} \text{ ns}$
- Implementation loss:
 - 0.3 for PL-single element SNSPDs
 - 1.2 for FMF-SNSPD array
- Assumes $\text{BER} \leq 10^{-6}$
- Margin $\geq 2 \text{ dB}$
- 230 kbps – 533 Mbps



Both systems show feasibility to achieve data rates into the 100s Mbps. The photonic lantern-based system outperforms the FMF/array system for lower data rates/input power.

Summary



- We have characterized the main loss mechanisms for two fiber-detector subsystems as part of a photon-counting optical receiver based (mostly) on commercially available components
- Losses due to coupling, blocking, and non-uniform signal splitting were quantified, for a range of input power and various D/r_0
- With optimal coupling, the receiver concept based on a FMF photonic lantern with 7 single-element SNSPDs has lower total losses for lower data rates and input powers
- For rates above ~ 200 Mbps the single FMF-SNSPD array system outperforms and can potentially achieve data rates up to 533 Mbps



Thank You!

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